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(71) Applicant *(for all designated States except US)*: **CONEXANT SYSTEMS, INC.** [US/US]; 4311 Jamboree Road, Dept. 927, MS M08-803, Newport Beach, CA 92660 (US).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **PULLEY, Douglas, Roger** [GB/GB]; 19 Prospect Place, Camden Road, Bath, Avon BA1 5JD (GB). **FOXCROFT, Thomas** [GB/GB]; 52B Pembroke Road, Bristol, Avon BS8 3DT (GB).

(74) Agents: **AKERS, Noel** et al.; Howrey Simon Arnold & White, CityPoint, One Ropemaker Street, London, Greater London EC2Y 9HS (GB).

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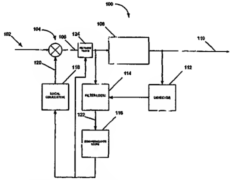
(54) Title: SYSTEM AND METHOD FOR DETECTING NARROWBAND INTERFERENCE IN A WIDEBAND OFDM SIGN AL BASED ON NORMALIZED SUBCARRIER AMPLITUDES




(57) Abstract: A system for and method of removing narrowband interference from a wideband signal (102). The wideband signal may be a multi-carrier signal representing a plurality of symbols, where one or more of the symbols each separately modulate a subcarrier within the multi-carrier signal. In one implementation, the wideband signal is an OFDM signal. A detector (112) analyzes one or more frequency bins of the signal to determine whether or not the narrowband interference has unduly corrupted a frequency bin. This determination is based on the number of subcarriers within each bin whose normalized amplitudes are below a first threshold. If said number is smaller than a second threshold, a bin is deemed uncorrupted.Logic then discards a frequency bin if the detector indicates that the frequency bin has been unduly corrupted by narrowband interference, and retains the frequency bin if the detector indicates that the frequency bin has not been unduly corrupted by narrowband interference. A combiner combines the retained frequency bins to produce an output signal. In one implementation, FFT logic (108) produces a frequency domain representation (110) of the wideband signal (102) from a time domain representation (106) of the signal. The frequency domain representation of the signal may be divided up into M frequency bins, wherein M is an integer of two or more. Filter logic (114) isolates each of the frequency bins from a time domain representation of the signal, and discards or retains a frequency bin based on the analysis performed by the detector on the frequency domain representation of the signal.

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# SYSTEM AND METHOD FOR DETECTING NARROWBAND INTERFERENCE IN A WIDEAND OFDM SIGNAL BASED ON NORMALIZED SUBCARRIER AMPLITUDE

This invention relates generally to wideband signals, and, more specifically, to removing narrowband interference from a wideband signal such as a multi-carrier signal.

A multi-carrier signal is one in which an incoming stream of bits or symbols is divided up into groupings, each with a lower data rate, with each grouping used to modulate a different carrier. The modulated signals are then combined together to form a wideband transmission signal. In the area of wireless communications, a multi-carrier signal is an attractive mechanism to deal with the problem of multi-path, in which multiple delayed echos of the original transmitted signal give rise to intersymbol interference. That is because the increased delay between successive symbols made possible by dividing the incoming data stream into groupings can be made large in relation to the duration of the time period over which the echos are received, thus reducing or eliminating the problem of intersymbol interference.

Orthogonal frequency division multiplexing (OFDM) is a form of multi-carrier signaling in which the groupings of a data stream modulate densely packed subcarriers with overlapping spectra, and in which modulation of the multiple subcarriers occurs algorithmically through fast Fourier transform (FFT) techniques. In one implementation of an OFDM transmitter, a serial-to-parallel converter divides an incoming stream of symbols into a plurality of parallel streams. An inverse fast Fourier transform (FFT) circuit then performs an inverse FFT on the parallel streams. A parallel-to-serial converter combines the inversely transformed streams in a serial stream. A modulator then modulates a carrier signal with the serial stream. The modulated carrier is then transmitted over the communications interface. OFDM is presently used for a variety of applications such as digital television transmission. In Europe, the standards for digital audio broadcasting (DAB) and digital video broadcasting – terrestrial (DVB-T) which have emerged are based on OFDM.

In OFDM, even though the spectra of the subcarriers overlap, orthogonality between the different groupings is maintained through the nature of the modulation which is performed, which is QAM, and also through appropriate spacing of the subcarriers. Together, these factors ensure that the spectra of adjacent subcarriers, which are in the form of a sinc function, are such that the peaks of a spectrum for one subcarrier lie on the zeroes of spectra for the other subcarriers. Moreover, even though the available number of subcarriers limit, as a practical matter, the extent to which intersymbol interference can be avoided, cyclic prefix guard bands are added in the time domain to the active zones representing each symbol to ensure that intersymbol interference is reduced to tolerable levels even with a limited number of subcarriers. Additional information on OFDM is available in "Data Transmission by Frequency-Division Multiplexing Using the Discrete Fourier Transform," S. B. Weinstein and P. M. Ebert, IEEE Transactions on Communication Technology, Vol. COM-19, No. 5, October 1971, pp. 628-634, which is hereby fully incorporated by reference herein as through set forth in full.

To function properly, the transmitter and receiver in a multi-carrier signaling communications system must be synchronized, both in time and in frequency. To synchronize itself, the receiver must acquire timing information from the multi-carrier signal. Unfortunately, due to narrowband interference of various forms, including co-channel interference from analog television signals, the acquisition of timing and/or synchronization information from the multi-carrier signal is often difficult.

The invention provides a system for and method of removing narrowband interference from a wideband signal. A representation of the signal may have one or more frequency bins. One or more of the frequency bins may each by analyzed by a detector to determine if it has been unduly corrupted by a narrowband interferer. If so, the content of the frequency bins may be removed from the signal, and, if not, the content of the frequency bins may be retained in the signal. The resulting signal, after removal of the frequency bins unduly corrupted by narrow band interferers, may then

be used for various applications such as the acquisition of timing and/or acquisition information.

The wideband signal may be a multi-carrier signal representing a plurality of symbols wherein one or more of the symbols separately modulate different subcarriers. A frequency domain signal may be derived from a time domain representation of the signal. The frequency domain signal may then be divided into frequency bins, and one or more of the frequency bins analyzed to determine if a narrowband interferer has unduly corrupted the contents of the frequency bin. If so, the contents of the frequency bin may be removed from a time domain representation of the signal, and if not, the contents of the frequency bin retained in the time domain representation of the signal.

The multi-carrier signal may be an OFDM signal representing a plurality of symbols wherein each of the symbols separately modulates a different subcarrier. In one example, 1702 subcarriers are each represented in the signal. A frequency domain representation of the signal may be derived by taking the fast Fourier transform ("FFT") of a time domain representation of the signal. The frequency domain representation of the signal may then be divided into frequency bins. In one example, 12 uniformly sized frequency bins are employed. The subcarriers within each of the frequency bins may be analyzed to determine if the frequency bin has been unduly corrupted by interference.

This analysis may occur by normalizing the amplitudes of each of the subcarriers within a frequency bin by the subcarrier having the largest amplitude. The cumulative distribution of the resulting normalized amplitudes may then be analyzed. If the number of subcarriers having an amplitude below a threshold amplitude is less than a second threshold value, the frequency bin may be deemed to be free from undue interference. However, if the number of subcarriers having an amplitude below the threshold amplitude is greater than or equal to the second threshold, the frequency bin may be deemed to have been unduly corrupted by interference.

One or more signals representing the results of this analysis may be provided to logic which, responsive to these one or more signals, removes from the signal those frequency bins deemed to have been unduly corrupted by interference, and retains in the signal those frequency bins deemed to be free from undue interference.

In one implementation, the logic is filter logic which functions by isolating one or more of the frequency bins from a time domain representation of the signal using or more filters, and then discards those frequency bins deemed to have been unduly corrupted by interference. A combiner combines the frequency bins which are retained to produce an output signal.

The filter logic may include a mixer which successively demodulates designated frequency bins to baseband. One or more digital filters may isolate in parallel the designated frequency bin and one or more additional frequency bins. Switches coupled to the outputs of the filters retain those frequency bins that are deemed to be free of undue interference, and remove those frequency bins deemed to have been unduly corrupted by interference. The retained frequency bins are combined, and modulated back to the frequency of the designated frequency bin. This process is may iterate one or more times until all the frequency bins have been covered.

Other systems, methods, features and advantages of the invention will be or will become apparent to one with skill in the art upon examination of the following figures and detailed description. It is intended that all such additional systems, methods, features and advantages be included within this description, be within the scope of the invention, and be protected by the accompanying claims.

The components in the figures are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention. In the figures, like reference numerals designate corresponding parts throughout the different views.

FIG. 1 is a simplified block diagram of an example environment of a system according to the invention.

FIG. 2A is a frequency domain representation of an embodiment of an orthogonal frequency division multiplexing ("OFDM") signal with N subcarriers, where N is an integer greater than 1.

FIG. 2B is a frequency domain representation of narrow band interference interposed on the OFDM signal of FIG. 2A.

FIG. 3A is a frequency domain representation of an embodiment of an OFDM signal divided up into M frequency bins, where M is an integer of two or more.

FIG. 3B is a representation of one example of a cumulative density function for a frequency bin which is free from the effects of undue interference.

FIG. 3C is a representation of one example of a cumulative density function for a frequency bin which has been unduly corrupted by interference.

FIGs. 4A-4E are block diagrams of embodiments of a system according to the invention for removing narrowband interference from a wideband signal.

FIGs. 5A-5C are block diagrams of embodiments of logic for removing undul corrupted frequency bin in a system according to the invention.

FIG. 6 is a flowchart of an embodiment of a method according to the invention.

FIGs. 7A-7E are representations in the frequency domain of frequency bins during the various iterations which may occur in one implementation of a system according to the invention.

An example of an application of the invention will now be described for the purpose of providing context and assisting in a greater understanding of the invention. However, it should be appreciated that the invention is not limited to this application, and that many other applications of the invention are possible.

The application which will be described is a system for synchronizing a local oscillator signal used for demodulating a wideband multi-carrier signal received over a communications channel. The channel may be a wireline or wireless communications channel. A block diagram of the system 100 is illustrated in Figure 1. The system may be part of a receiver or transceiver. The multi-carrier signal is received over a communications channel and provided on one or more signal lines 102 to demodulator 104. The other input to demodulator 104 is a local oscillator signal provided by local oscillator 118. This signal is provided as an input to the demodulator 104 over one or more signal lines 120.

The demodulator 104 demodulates the received signal using the local oscillator signal to produce an output signal having a high frequency component and a baseband component. The high frequency component is filtered out using a low pass filter (not shown). The result is a baseband signal provided on one or more signal lines 106.

The baseband signal is input to transformation circuitry 108. In one implementation, where the received signal is an OFDM signal, transformation circuitry 108 is fast Fourier transform (FFT) circuitry configured to take the FFT of the baseband signal, thereby inverting the effects of the inverse FFT typically applied at the transmitter. The output of transformation circuitry is provided on one or more signal lines 110.

The baseband signal provided on one or more signal lines 106 is a time domain signal representing a plurality of symbols, where one or more of the symbols may each modulate separate subcarriers within the signal. However, the signal

provided on one or more signal lines 110 may be a frequency domain signal representing the symbols. This signal is provided as an input to detector 112. Detector 112 detects whether any frequency portions of the frequency domain representation of the signal have been unduly corrupted by narrowband interference, and signals filter logic 114 to remove these portions from the time domain representation of the signal.

The resulting time domain signal is provided as an input to one or more synchronization loops 116. These one or more loops 116 acquire timing and/or synchronization information from the resulting signal, and, responsive thereto, cause local oscillator 118 to adjust the phase or frequency of the local oscillator signal 120 until synchronization is achieved.

In addition, the output of the synchronization loops 116 drives re-timing block 124, which adjusts the timing of the signal 106 until synchronization is achieved. In one implementation, the re-timing block 124 is a sinc interpolator.

Figure 2A is a frequency domain representation of one embodiment of a wideband signal 200. This embodiment of the signal 200 has N subcarriers, where N is an integer of 1 or more, which are identified with numerals 202a, 202b, 202c. One or more of the symbols may each be modulated onto a separate one of the subcarriers. In one example, the signal is an OFDM signal used for DVB-T applications in the United Kingdom. In this example, N, the number of subcarriers, may be 1702 for a 2K FFT (which allows a maximum of 2048 subcarriers), or 6820 for an 8K FFT (which allows a maximum of 8192 subcarriers).

Figure 2B illustrates narrowband interference 204 interposed on the signal of Figure 2A. As illustrated, the narrowband interference 204 unduly corrupts or otherwise interferes with one or more of the subcarriers 202d, 202e.

The invention provides a system for and method of removing narrowband interference from a wideband signal, an example of which is illustrated in Figures 2A

and 2B. In the application illustrated in Figure 1, the system may comprise the elements 114 and 112, and output the signal 122 from which timing and/or synchronization is acquired.

A first embodiment of a system according to the invention is illustrated in Figure 4A. As illustrated, the system 400 comprises detector 408 and filter logic 402. A frequency domain representation of a wideband signal is provided to the detector 404 over one or more signal lines 408, and a time domain representation of the signal is provided to the filter logic 402 over one or more signal lines 406. The detector 404 is configured to divide the frequency domain signal into a plurality M of frequency bins, where M is an integer greater than 1, and separately analyze one or more of the frequency bins to detect the presence or absence of undue narrowband interference. The results of this analysis may be provided to filter logic 402 in the form of one or more signals provided over one or more signal lines 410. Responsive thereto, filter logic 402 removes from the time domain representation of the signal the content of those frequency bins which have been corrupted due to the presence of the narrowband interferer. The resulting signal may then be output on one or more signal lines 412.

In the case where the wideband signal is comprised of a plurality of subcarriers, the frequency bins may each include one or more of the subcarriers. It is also possible for one or more of the frequency bins to entirely exclude subcarriers. In one example, where the signal is an OFDM signal employing 1702 subcarriers, the distribution may be such that each of the frequency bins contain about 142 subcarriers, although other distributions are possible.

The detector 404 may analyze the subcarriers within a frequency bin to detect the presence or absence of undue narrowband interference within the frequency bin. In one embodiment, the detector 404 normalizes the amplitudes of each of the subcarriers within a frequency bin with the largest such amplitude, determines the cumulative distribution of the normalized amplitudes of the subcarriers within a frequency bin, and uses this information to detect the presence or absence of undue

interference. This is possible since the distribution will measurably differ depending on whether or not narrow band interference is present.

In one example, the detector 404 may determine from the cumulative distribution the number of subcarriers whose normalized amplitude falls below a threshold amplitude. If this value falls below a second threshold, the frequency bin is deemed to be free from undue interference, and if this value equals or exceeds the second threshold, the frequency bin is deemed to have been unduly corrupted by narrowband interference.

This mode of analysis can be further explained with the aid of Figures 3B and 3C. Figure 3B illustrates an idealized example of the normalized cumulative distribution that may occur for a frequency bin that is free from undue interference. The horizontal axis represents normalized amplitude, and the vertical axis represents the cumulative number or percentage of subcarriers within the frequency bin that have normalized amplitudes that fall below a specified point. Each point on the distribution curve thus represents the number of subcarriers within the frequency bin having a normalized amplitude that falls below a specified normalized amplitude corresponding to the point. By definition, and as illustrated in the figure, the maximum normalized amplitude along the horizontal axis is 1.0.

This example assumes that each symbol is represented by a 64-QAM constellation point (having complex I and Q values) modulated onto a subcarrier, although it should be appreciated that other forms of modulation are possible, e.g., QPSK, 16-QAM, etc. The amplitude of a subcarrier can be computed using the I and Q values of the constellation point as follows: $\sqrt{I^2 + Q^2}$. In the 64-QAM case, there are three possible power levels. Accordingly, the normalized cumulative curve illustrated in Figure 3B, consists of three points, identified respectively with numerals 302a, 302b, and 302c, where each of the points represents the number of subcarriers within the frequency bin having an amplitude that falls below the amplitude represented by the point. Since the frequency bin is free from undue interference,

there are only three points represented. An amplitude threshold $A_{THRESH}$ can be determined, identified in the figure with numeral 304. The number of subcarriers within the frequency bin having a normalized amplitude below this threshold is zero, indicating that the frequency bin is free from undue interference.

An example of the cumulative distribution for a frequency bin unduly corrupted by interference is illustrated in Figure 3C. A characteristic of such a distribution is that a substantial number of subcarriers will have normalized amplitudes in the lower region 306 of the curve. That is because the narrowband interference will typically represent a large spike in amplitude relative to the subcarriers. Therefore, normalizing the amplitudes of these subcarriers with that of the spike will drive a lot of these subcarriers to the lower region 306 of the curve.

The number of subcarriers V in this example which have a normalized amplitude below $A_{THRESH}$ may be determined and compared with a second threshold $N_{THRESH}$. Since V is assumed to be greater than $N_{THRESH}$, the frequency bin is deemed to have been unduly corrupted by narrowband interference.

Turning back to Figure 4A, the filter logic 402 receives the results of this analysis over one or more signal lines 410, and, responsive thereto, removes all or a substantial portion or at least some of the content of the frequency bins corrupted by interference from a time domain representation of the signal. For purposes of this disclosure, the term "logic" includes hardware, software, and a combination of hardware and software. In addition, the phrase "filter logic" is intended to include both analog and digital designs, as well as combinations of analog and digital designs.

A first embodiment of filter logic 402 is illustrated in Figure 5A. As illustrated, in this embodiment, the logic comprises of plurality of filters 502a, 502b, 502c, equal in number to M, the number of frequency bins into which the frequency domain representation of the signal is divided. Each of these filters is provided in parallel the time domain representation of the signal over one or more signal lines 406. Each filter is configured to filter out and isolate the frequency content of its

corresponding frequency bin. Thus, for example, with reference to both Figures 5A and 3A, filter 502a might be configured to isolate the frequency content of frequency bin 304a, filter 502b might be configured to isolate the frequency content of frequency bin 304b, and filter 502c might be configured to isolate the frequency content of frequency bin 304c. For purposes of this disclosure, and in acknowledgement of the limitations of real world filter design, the term "isolate" does not require precise isolation of the full frequency content of the frequency bin, but a substantial portion of the frequency content of the frequency bin consistent with tolerances for filter passbands which are acceptable in the trade.

Turning back to Figure 5A, the outputs of the filters 502a, 502b, and 502c are each provided to separate ones of switches 504a, 504b, and 504c, each of which is controllable by a corresponding output of detector 404 provided on one or more signal lines 410. If the corresponding output of detector 404 indicates that the frequency bin has been unduly corrupted by narrowband interference, the corresponding switch is opened, and if the corresponding output of detector 404 indicates that the frequency bin is free of such interference, the corresponding switch is closed. The result is that the frequency content of those frequency bins which are free from undue interference are provided to the outputs of the switches, while the frequency content of those frequency bins which have been corrupted by interference are discarded. For purposes of this disclosure, the term "switch" encompasses hardware switches, software switches, or combinations of hardware and software switches.

The outputs of the switches are provided in parallel to combiner 506, which combines the signals provided on these outputs, and outputs the combined signal on one or more signal lines 412. The result of the foregoing is a time domain representation of the wideband signal where the effects of narrowband interference have been substantially removed.

Figure 5B illustrates a second embodiment of the filter logic 402 which, compared to the embodiment of Figure 5A, may require less chip space to implement, but which may also have a lower throughput.

As illustrated, in this embodiment, the filter logic 402 comprises a first mixer 508, which has a tunable local oscillator (LO) input 510, a low pass filter 512, a second mixer 514, which also has a tunable LO input 516, a switch 518 controllable by the one or more signal lines 410 from detector 404, and a combiner 520. The local oscillator 510 is tunable to a frequency, such as the center frequency, corresponding to any of the frequency bins, and the mixer 508 is configured to demodulate the frequency content of any of the frequency bins down to baseband. The output of mixer 508 includes this baseband component, but also includes a high frequency component which is filtered out by low pass filter (LPF) 512. The resulting baseband component is input to mixer 514, the local oscillator input of which is also tunable to a frequency, such as the center frequency, corresponding to any of the frequency bins. In operation, the local oscillator input 516 is tuned to the same frequency as local oscillator input 510. Consequently, mixer 514 functions to modulate the baseband signal output by LPF 512 back to its original frequency. The result is that the signal provided on signal line 522 is a time domain representation of the frequency content of one of the frequency bins. By successively tuning the local oscillator inputs 510, 516 to successive frequencies corresponding to each of the frequency bins, the time domain representation of the frequency content of each of the frequency bins may be successively provided on signal line 522.

In tandem with the tuning of the local oscillator signals 510, 516, the switch 518 may be controlled to successively open or close under the direction of the output of detector 404. This allows the frequency content of a frequency bin to pass serially to combiner 520 if the frequency bin is free from undue interference, or to discard the frequency content of the frequency bin if it has been unduly corrupted by interference. Combiner 520 then combines the frequency content of those frequency bins which are free from undue interference, and provides a time domain representation of the same on one or more signal lines 412.

A third embodiment of filter logic 402 is illustrated in Figure 5C. This embodiment is configured for the case in which the frequency domain representation of the wideband signal is divided into 12 frequency bins, but it should be appreciated

that the invention encompasses embodiments where more or less frequency bins are employed. Compared to the embodiment of Figure 5B, this embodiment may have higher throughput, and compared to the embodiment of Figure 5C, this embodiment may consume less chip space.

As illustrated, a time domain representation of the wideband signal is input to mixer 522. The local oscillator input to mixer 522, identified with numeral 524, is tunable to a frequency, such as a center frequency, corresponding to each of the frequency bins. In operation, the LO input 524 to mixer 522 is set to a frequency, such as a center frequency, corresponding to one of the frequency bins. The frequency content of the frequency bin to which the local oscillator is tuned is mixed down to baseband, and the other frequency bins are also mixed down to lower frequencies. The output of the mixer 522 is input in parallel to each of the three filters 526a, 526b, 526c, each of which isolates the frequency content of a separate one of the frequency bins after mixing. Filter 526b may be a lowpass filter which isolates the frequency bin which has been mixed down to baseband. Filter 526a may be a bandpass filter which isolates a frequency bin which has a lower (typically negative) frequency than the frequency bin mixed down to baseband. Filter 526c may be a bandpass filter which isolates a frequency bin having a higher frequency than the frequency bin mixes down to baseband.

The outputs of the filters 526a, 526b, 526c are each input to corresponding ones of switches 528a, 528b, 528c, each is which is controllable responsive to the corresponding output of detector 404 indicating whether or not the corresponding frequency bin is free from or subject to undue interference. If the frequency bin is deemed to be subject to undue interference, the corresponding switch is opened, thereby causing the frequency content of the frequency bin to be discarded. If the frequency bin is deemed to be free from undue interference, the corresponding switch is closed, thereby retaining the frequency content of the frequency bin.

The outputs of the switches 528a, 528b, 528c are provided in parallel to combiner 530 which combines those of the three frequency bins under consideration

which are free from undue interference, and provides the combined signal to mixer 532. The LO input 534 to mixer 532 is tunable. In operation, it is typically tuned to the same frequency as the LO signal 524. The result is that those of the three frequency bins which are retained are restored to their original frequency levels. The resulting signal is then provided to combiner 536 for combining with information relating to the other frequency bins.

The filter logic 402 in this embodiment is iterative. During each iteration, three of the frequency bins are handled. Thus, for a wideband signal having a total of 12 frequency bins, four iterations of the filter logic 402 are required to handle all the frequency bins.

With reference to Figure 7A, for example, in a first iteration, the frequency bins 702a(1), 702b(1), and 702c(1) are handled. In this scenario, the LO signal 524 may be tuned to the center frequency of the frequency bin 702b(1). As a result, the frequency bin 702b(1) may be demodulated down to baseband frequencies, the frequency bin 702a(1) may be demodulated down to negative frequencies below baseband frequencies, and the frequency bin 702c(1) may be demodulated down to frequencies above baseband frequencies. Filter 526a is configured to isolate demodulated frequency bin 702a(1); filter 526b is configured to isolate demodulated frequency bin 702b(1); and filter 526c is configured to isolate demodulated frequency bin 702c(1).

The state of the switches 528a, 528b, 528c is such that only those frequency bins deemed to be free from undue interference are retained. These frequency bins are combined by combiner 530 and then modulated back to their original frequencies by mixer 532. The modulated signal from mixer 532 is input to and retained by combiner 536 for combining with additional information for the other frequency bins to be provided in the future.

With reference to Figure 7B, in a second iteration, the frequency bins 702a(2), 702b(2), and 702c(2) are handled. In this scenario, the LO signal 524 may be tuned to

the center frequency of the frequency bin 702b(2). As a result, the frequency bin 702b(2) may be demodulated down to baseband frequencies, the frequency bin 702a(2) may be demodulated down to negative frequencies below baseband frequencies, and the frequency bin 702c(2) may be demodulated down to frequencies above baseband frequencies. Filter 526a is configured to isolate demodulated frequency bin 702a(2); filter 526b is configured to isolate demodulated frequency bin 702b(2); and filter 526c is configured to isolate demodulated frequency bin 702c(2).

The state of the switches 528a, 528b, 528c is such that only those frequency bins deemed to be free from undue interference are retained. These frequency bins are combined by combiner 530 and then modulated back to their original frequencies by mixer 532. The modulated signal from mixer 532 is input to and retained by combiner 536 for combining with the information provided in the first iteration as well as additional information from future iterations.

With reference to Figure 7C, for example, in a third iteration, the frequency bins 702a(3), 702b(3), and 702c(3) are handled. In this scenario, the LO signal 524 may be tuned to the center frequency of the frequency bin 702b(3). As a result, the frequency bin 702b(3) may be demodulated down to baseband frequencies, the frequency bin 702a(3) may be demodulated down to negative frequencies below baseband frequencies, and the frequency bin 702c(3) may be demodulated down to frequencies above baseband frequencies. Filter 526a is configured to isolate demodulated frequency bin 702a(3); filter 526b is configured to isolate demodulated frequency bin 702b(3); and filter 526c is configured to isolate demodulated frequency bin 702c(3).

The state of the switches 528a, 528b, 528c is such that only those frequency bins deemed to be free from interference are retained. These frequency bins are combined by combiner 530 and then modulated back to their original frequencies by mixer 532. The modulated signal from mixer 532 is input to and retained by combiner 536 for combining with the information from the first and second iterations as well as additional information to be provided from a fourth iteration.

With reference to Figure 7D, in the fourth iteration, the frequency bins 702a(4), 702b(4), and 702c(4) are handled. In this scenario, the LO signal 524 may be tuned to the center frequency of the frequency bin 702b(4). As a result, the frequency bin 702b(4) may be demodulated down to baseband frequencies, the frequency bin 702a(4) may be demodulated down to negative frequencies below baseband frequencies, and the frequency bin 702c(4) may be demodulated down to frequencies above baseband frequencies. Filter 526a is configured to isolate demodulated frequency bin 702a(4); filter 526b is configured to isolate demodulated frequency bin 702b(4); and filter 526c is configured to isolate demodulated frequency bin 702c(4).

The state of the switches 528a, 528b, 528c is such that only those frequency bins deemed to be free from undue interference are retained. These frequency bins are combined by combiner 530 and then modulated back to their original frequencies by mixer 532. The modulated signal from mixer 532 is input to and retained by combiner 536 for combining with the information from the first, second, and third iterations. After the fourth iteration, the combined signal from the four iterations may be output on one or more signal lines 412.

In one implementation, the filters 526a, 526b, 526c are digital filters. In this implementation, filter 526b is a real filter, and filters 526a and 526c are complex filters. Moreover, filters 526a and 526c may both be implemented by simple modifications to filter 526b.

To explain this, consider that the spectrum for each of the cases illustrated in Figures 7A-7D after mixing by mixer 522 can be represented as illustrated in Figure 7E, where the sampling frequencies for the frequency bins 702a, 702b, 702c bear a relationship to one another. In one example, if the sampling frequency for frequency bin 702b is $f_S$, then the sampling frequency of frequency bin 702c may be $5/4 \bullet f_S$, and that for frequency bin 702a may be $3/4 \bullet f_S$.

The filter 526b for extracting the frequency bin 702b may be a real filter, and that for extracting the frequency bins 702a and 702c, identified with numerals 526a and 526c, may be complex filters whose coefficients are derived from that of the real filter.

Consider the example discussed earlier where the sampling frequency for frequency bin 702b is $f_S$, the sampling frequency of frequency bin 702c may be $5/4 \bullet f_S$, and that for frequency bin 702a may be $3/4 \bullet f_S$. If the coefficients for real filter 526b are as follows:

$$\ldots C3, C2, C1, C0, C1, C2, C3 \ldots$$

then those for complex filter 526c may be represented as follows:

$$\ldots C3e^{j\pi/2}, C2e^{-j\pi}, C1e^{-j\pi/2}, C0e^{j0}, C1e^{j\pi/2}, C2e^{j\pi}, C3e^{-j\pi/2} \ldots$$

while those for complex filter 526a may be represented as follows:

$$\ldots C3e^{-j\pi/2}, C2e^{j\pi}, C1e^{j\pi/2}, C0e^{j0}, C1e^{-j\pi/2}, C2e^{-j\pi}, C3e^{j\pi/2} \ldots$$

Given the following identities: $e^{j0} = 1$; $e^{j\pi/2} = j$; $e^{j\pi} = -1$; $e^{-j\pi/2} = -j$; the coefficients for complex filter 526c may be re-expressed as follows:

$$\ldots jC3, -C2, -jC1, C0, jC1, -C2, -jC3 \ldots$$

while those for complex filter 526a may be re-expressed as follows:

$$\ldots -jC3, -C2, jC1, C0, -jC1, -C2, jC3 \ldots$$

The real filter 526b may be implemented by multiplying both the real and imaginary (I, Q) components of a symbol by the filter coefficients. From the foregoing, it can be seen that the filters 526a, 526c may be derived from these same multiplications. Thus, the three filters 526a, 526b, 526c in this implementation may be replaced by a modified filter structure in which the three filtering operations are performed from the same set of multiplications.

Turning back to Figure 4A, some other embodiments of a system for removing substantial narrowband interference from a wideband signal will now be discussed. Figure 4B illustrates a second embodiment of such a system. As can be seen, this embodiment is identical to the first except that the transformation logic 422 is

included for determining a frequency domain representation of the wideband signal from the time domain representation of the signal, and outputting the frequency domain representation on one or more signal lines 408. In one implementation, this transformation logic 422 may comprise FFT logic for determining the FFT of the time domain representation of the wideband signal.

Figure 4C illustrates a third embodiment of a system according to the invention. In this embodiment, compared to the previous two embodiments, the detector 424 is configured to receive a time domain representation of the wideband signal rather than a frequency domain representation of the signal. Other than this difference, this embodiment of the system functions identically to that of the other two embodiments. In one implementation, the detector 424 may be formed by combining the functionality of the transformation logic 422 and the detector 404 in the embodiment of Figure 4B. In another implementation, the detector 424 may isolate the frequency content of the various frequency bins in the time domain through suitable filters, and then analyze the time domain representation of the various frequency bins to determine if a wideband interferer is unduly present or not. If so, the frequency bin is discarded, and if not, the frequency bin is retained.

Figure 4D illustrates a fourth embodiment of a system according to the invention. In this embodiment, transformation logic 422 forms a frequency domain representation of the wideband signal which is provided as an input to detector 404 and first logic 426. The detector 404 functions as described in the previous embodiments and provides an indication over one or more signal lines 410 which frequency bins have been unduly corrupted by narrowband interference and which are free from such undue interference. Responsive thereto, first logic 426 receives the frequency domain representation of the signal, and simply zeroes out or otherwise eliminates the frequency domain coefficients of the frequency bins that have been unduly corrupted by noise. The resulting signal may then be provided to inverse transformation logic 428 which performs the inverse of the transformation performed by logic 422. The result is a time domain representation of the wideband signal on

one or more signal lines 430 in which the effects of narrowband interference have been substantially removed.

Figure 4E illustrates a fifth embodiment of a system according to the invention. In this embodiment, transformation logic 422 is omitted, and the input to the system is a frequency domain representation of wideband signal provided on one or more signal lines 408. Otherwise, this embodiment is identical to the previous embodiment.

Figure 6 is a flowchart of one embodiment of a method according to the invention. As illustrated, the embodiment begins in step 602, where one or more frequency bins of a representation of a wideband signal are analyzed to determine if a narrowband interferer has unduly corrupted the frequency bin or not. The representation of the signal may be a frequency or time domain representation of the signal. In step 604, a frequency bin is discarded if the previous step indicates that a narrowband interferer has unduly corrupted the frequency bin, and the frequency bin is retained if the previous step indicates that the frequency bin is free from undue narrowband interference. Step 604 is followed by step 606, in which the retained frequency bins are combined to form an output signal. This embodiment of the method may then iterate continuously, periodically, or intermittently.

While various embodiments of the invention have been described, it will be apparent to those of ordinary skill in the art that many more embodiments and implementations are possible that are within the scope of this invention.

## Claims

1. A method of removing narrowband interference from a wideband signal, the wideband signal having a plurality of frequency bins, the method comprising the steps of:

analyzing one or more of the frequency bins to determine whether or not narrowband interference has unduly corrupted the frequency bin or not;

discarding those frequency bins for which the previous step indicates that narrowband interference has unduly corrupted the frequency bin, and retaining those frequency bins for which the previous step indicates the narrowband interference has not unduly corrupted the frequency bin; and

combining the retained frequency bins to form an output signal.

2. The method of claim 1 wherein the analyzing step comprises determining whether or not a frequency bin has been unduly corrupted by narrowband interference responsive to the cumulative number of subcarriers within the frequency bin having a normalized amplitude which falls below a predetermined threshold.

3. The method of claim 2 wherein the amplitudes of one or more of the subcarriers within a frequency bin are normalized using the largest subcarrier amplitude within the frequency bin.

4. The method of claim 1 wherein the analyzing step is performed on a frequency domain representation of the signal.

5. The method of claim 1 wherein the analyzing step is performed on a time domain representation of the signal.

6. The method of claim 1 wherein the discarding step comprises filtering a time domain representation of the wideband signal to isolate one or more of the

frequency bins, and discarding a frequency bin if the analyzing step indicates that the frequency bin has been unduly corrupted by narrowband interference.

7. A method of removing narrowband interference from a wideband signal comprising the steps of:

analyzing one or more frequency bins of a frequency domain representation of the signal to determine whether or not narrowband interference has unduly corrupted a frequency bin;

discarding a frequency bin from a time domain representation of the signal if the previous step indicates that the frequency bin has been unduly corrupted by narrowband interference, and retaining a frequency bin in a time domain representation of the signal if the previous step indicates that the frequency bin has not been unduly corrupted by narrowband interference; and

combining the retained frequency bins to produce an output signal.

8. A method of removing narrowband interference from a wideband signal, the wideband signal having a plurality of frequency bins, the method comprising the steps of:

a step for analyzing one or more of the frequency bins to determine whether or not narrowband interference has unduly corrupted the frequency bin or not;

a step for discarding those frequency bins for which the previous step indicates that narrowband interference has unduly corrupted the frequency bin, and retaining those frequency bins for which the previous step indicates the narrowband interference has not unduly corrupted the frequency bin; and

a step for combining the retained frequency bins to form an output signal.

9. A system for removing narrowband interference from a wideband signal, the wideband signal having one or more frequency bins, comprising:

a detector for analyzing one or more of the frequency bins to determine whether or not the frequency bins have been unduly corrupted by narrowband interference; and

logic for discarding a frequency bin if the detector indicates that the frequency bin has been unduly corrupted by narrowband interference, and retaining a frequency bin if the detector indicates that the frequency bin has not been unduly corrupted by narrowband interference; and

a combiner for combining the retained frequency bins to produce an output signal.

**10.** The system of claim 9 wherein the detector is configured to analyze the one or more frequency bins as derived from a frequency domain representation of the signal.

**11.** The system of claim 9 wherein the detector is configured to analyze the one or more frequency bins as derived from a time domain representation of the signal.

**12.** The system of claim 9 wherein the logic is filter logic configured to isolate a frequency bin by filtering it from a time domain representation of the signal.

**13.** The system of claim 9 wherein the logic is configured to isolate a frequency bin by extracting on or more coefficients from a frequency domain representation of the signal.

**14.** The system of claim 9 wherein one or more of the frequency bins each have a plurality of subcarriers, one or more of the subcarriers have an amplitude, and the detector is configured to determine whether or not a frequency bin has been unduly corrupted by narrowband interference responsive to the cumulative number of subcarriers within the frequency bin having a normalized amplitude which falls below a predetermined threshold.

**15.** The system of claim 14 wherein the amplitudes of the subcarriers within a frequency bin are normalized using the largest subcarrier amplitude within the frequency bin.

**16.** The system of claim 9 wherein the logic comprises N filters, wherein N is an integer of one or more, the wideband signal comprises M frequency bins, where M is an integer of two or more, and N is less than M.

**17.** The system of claim 16 wherein the N filters are each digital filters.

**18.** The system of claim 17 wherein one of the filters is a real filter, the other filters are complex filters, and the coefficients of the complex filters are each derived from that of the real filter.

**19.** The system of claim 18 wherein each of the coefficients of the complex filters are derived from a coefficient of the real filter using one or more of the following operations: setting the coefficient equal to the real coefficient, inverting the sign of the real coefficient or multiplying the real coefficient by $\pm j$.

**20.** A system for removing narrowband interference from a wideband signal, the wideband signal having one or more frequency bins, comprising:

a detector for analyzing one or more of the frequency bins from a frequency domain representation of the signal to determine whether or not the frequency bins have been unduly corrupted by narrowband interference; and

filter logic for discarding from a time domain representation of the signal a frequency bin if the detector indicates that the frequency bin has been unduly corrupted by narrowband interference, and retaining a frequency bin if the detector indicates that the frequency bin has not been unduly corrupted by narrowband interference; and

a combiner for combining the retained frequency bins to produce an output signal.

**21.** A system for removing narrowband interference from a wideband signal, the wideband signal having one or more frequency bins, comprising:

means for analyzing one or more of the frequency bins to determine whether or not the frequency bins have been unduly corrupted by narrowband interference; and

means for discarding a frequency bin if the detector indicates that the frequency bin has been unduly corrupted by narrowband interference, and retaining a frequency bin if the detector indicates that the frequency bin has not been unduly corrupted by narrowband interference; and

means for combining the retained frequency bins to produce an output signal.

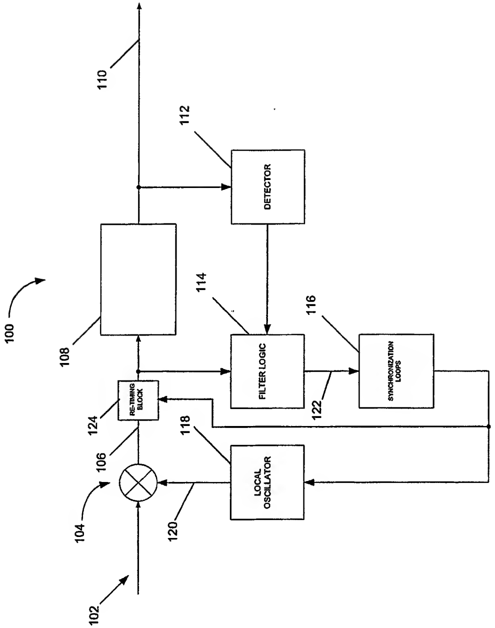
100
102
104
106
124
RE-TIMING BLOCK
108
110
112
DETECTOR
114
FILTER LOGIC
116
SYNCHRONIZATION LOOPS
122
118
LOCAL OSCILLATOR
120

FIGURE 1

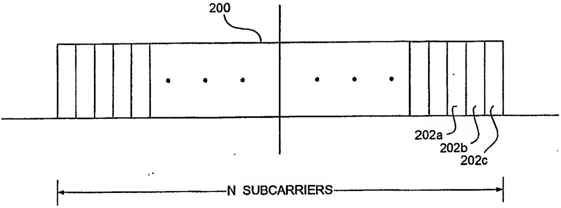


FIGURE 2A

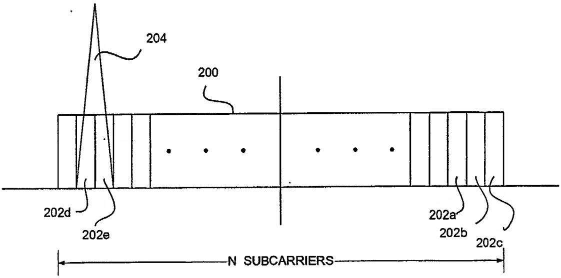


FIGURE 2B

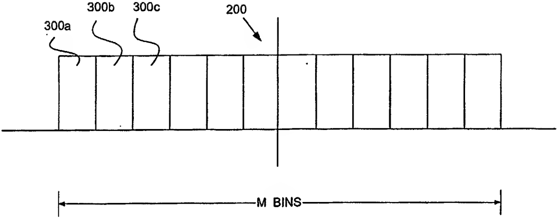


FIGURE 3A

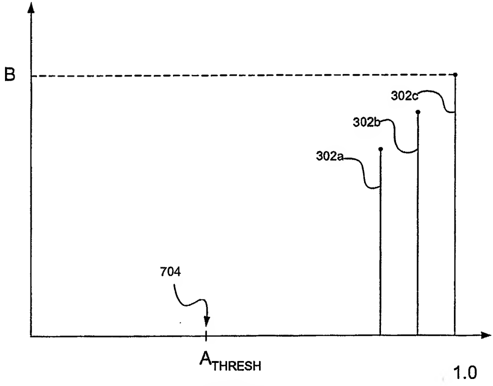


FIGURE 3B

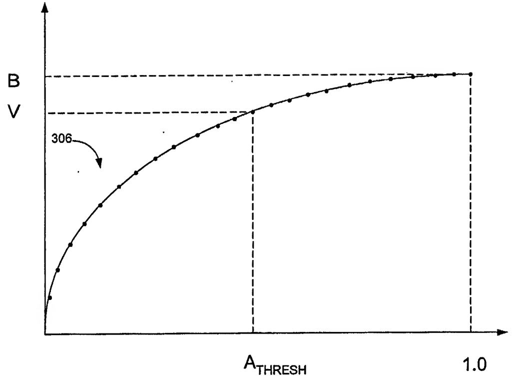


FIGURE 3C

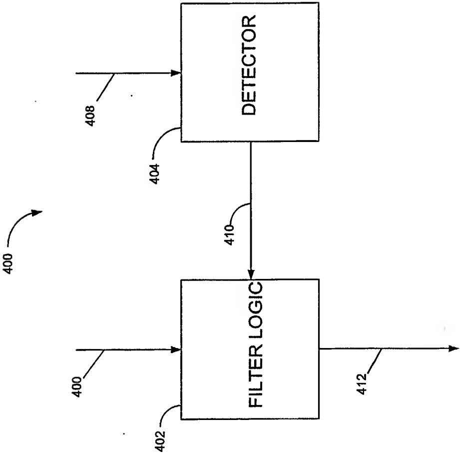


FIGURE 4A

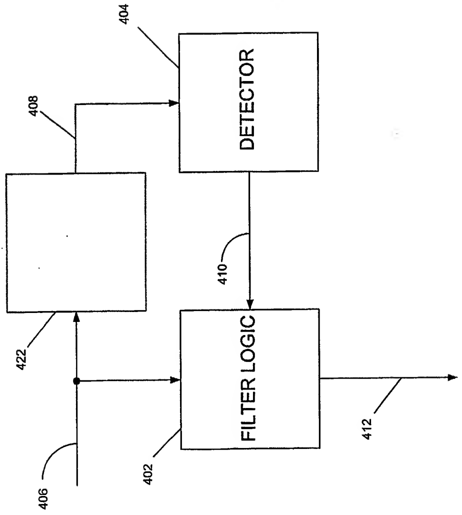


FIGURE 4B

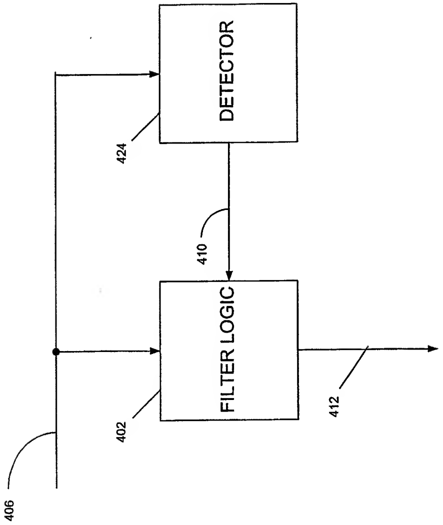


FIGURE 4C

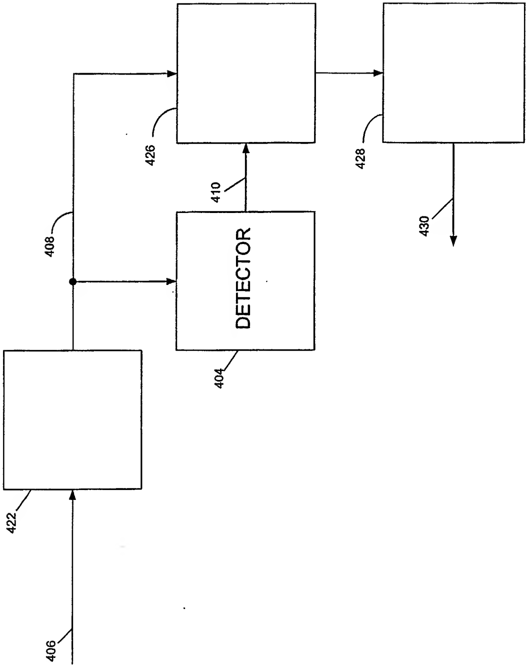


FIGURE 4D

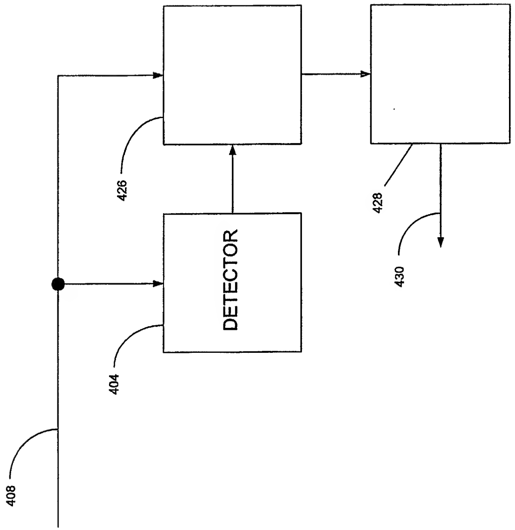


FIGURE 4E

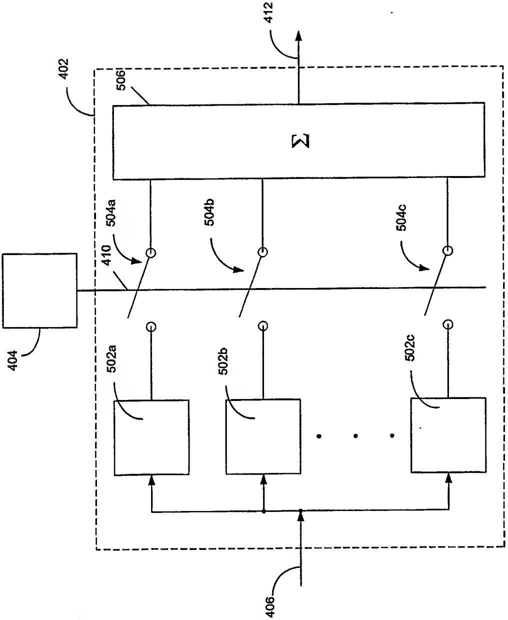


FIGURE 5A

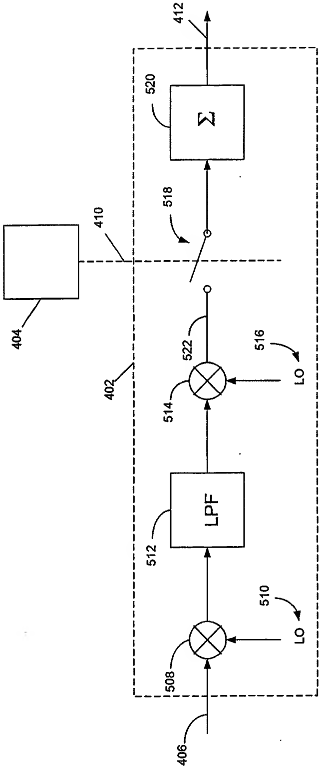


FIGURE 5B

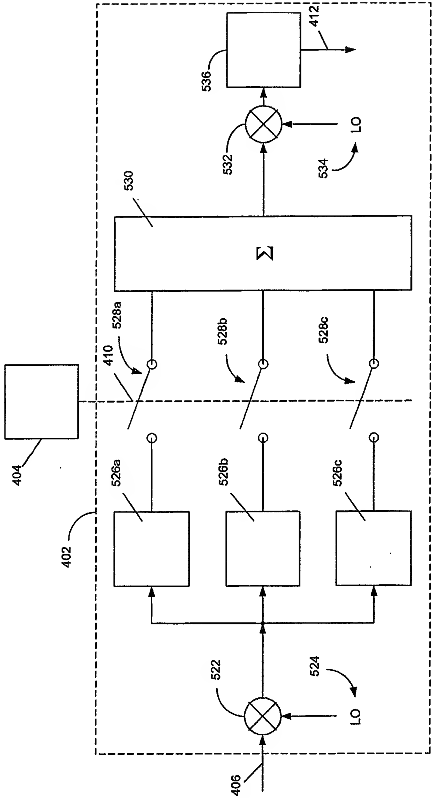
404
402
406
522
524
LO
526a
526b
526c
410
528a
528b
528c
530
Σ
532
534
LO
536
412

FIGURE 5C

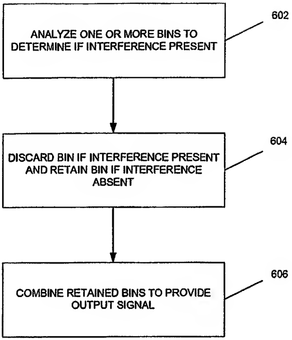
ANALYZE ONE OR MORE BINS TO DETERMINE IF INTERFERENCE PRESENT
602
DISCARD BIN IF INTERFERENCE PRESENT AND RETAIN BIN IF INTERFERENCE ABSENT
604
COMBINE RETAINED BINS TO PROVIDE OUTPUT SIGNAL
606

FIGURE 6

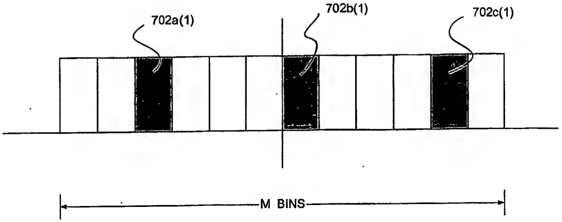


FIGURE 7A

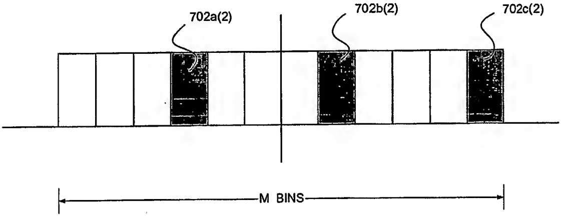


FIGURE 7B

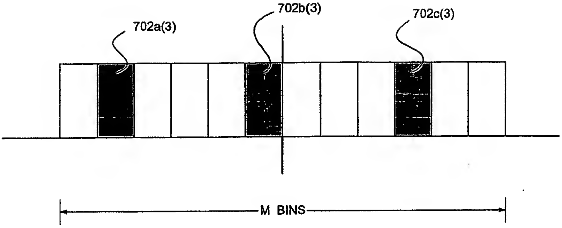


FIGURE 7C

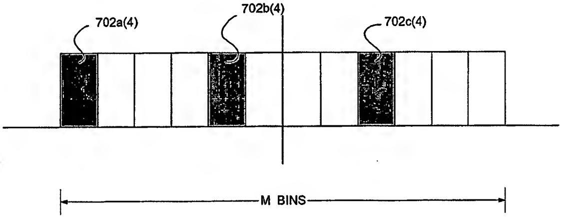


FIGURE 7D

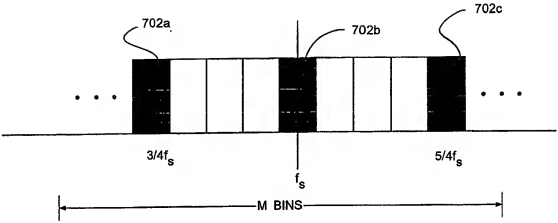


FIGURE 7E

# INTERNATIONAL SEARCH REPORT

PCT/GB 02/01783

**A. CLASSIFICATION OF SUBJECT MATTER**
IPC 7 H04L27/26

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category ° | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X | HSU-FENG HSIAO ET AL: "Narrow-band interference rejection in OFDM-CDMA transmission system" CIRCUITS AND SYSTEMS, 1998. ISCAS '98. PROCEEDINGS OF THE 1998 IEEE INTERNATIONAL SYMPOSIUM ON MONTEREY, CA, USA 31 MAY-3 JUNE 1998, NEW YORK, NY, USA,IEEE, US, 31 May 1998 (1998-05-31), pages 437-440, XP010289540 ISBN: 0-7803-4455-3 page 437, left-hand column -page 439, left-hand column --- | 1-4, 7-10, 13-15, 20,21 |

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 28 October 2002 | 06/11/2002 |

| Name and mailing address of the ISA | Authorized officer |
|---|---|
| European Patent Office, P.B. 5818 Patentlaan 2<br>NL – 2280 HV Rijswijk<br>Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,<br>Fax: (+31-70) 340-3016 | Marzenke, M |

Form PCT/ISA/210 (second sheet) (July 1992)

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

| Category ° | Citation of document, with indication,where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X | RANHEIM A: "Narrowband interference rejection in direct-sequence spread-spectrum system using time-frequency decomposition" IEE PROCEEDINGS: COMMUNICATIONS, INSTITUTION OF ELECTRICAL ENGINEERS, GB, vol. 142, no. 6, 1 December 1995 (1995-12-01), pages 393-400, XP006003956 ISSN: 1350-2425 page 393, left-hand column -page 396, left-hand column | 1,5-9, 11,12, 16-21 |
| A | EP 1 043 875 A (NEC USA INC) 11 October 2000 (2000-10-11) page 7, line 38 -page 8, line 16; figures 1,2 | 1-21 |
| A | WO 99 03227 A (NOKIA TELECOMMUNICATIONS OY ;OKSANEN LAURI (FI)) 21 January 1999 (1999-01-21) abstract page 2, line 18 - line 21 page 3, line 7-9 page 5, line 1 - line 14 page 6, line 1 -page 7, line 23 | 1-21 |

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PCT/GB 02/01783

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| | | | AU | 7920298 A | 08-02-1999 |
| | | | CN | 1231095 T | 06-10-1999 |
| | | | EP | 0929960 A2 | 21-07-1999 |
| | | | WO | 9903227 A2 | 21-01-1999 |
| | | | JP | 2001506468 T | 15-05-2001 |
| | | | NO | 990894 A | 25-02-1999 |